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Preliminary economic assessment of a polymer production plant in batch and continuous manufacturing

KEYWORDS: Process intensification, polymer, batch, continuous manufacturing, economic assessment, flow chemistry.

ABSTRACT

While continuous manufacturing is more efficient than batch processes, the impact of economic uncertainty can kill any project before it has even started. This document assesses three different methods for estimating capital investments and two polymer plants are used as case study (batch versus continuous manufacturing). Capital costs were determined using capacity, parametric and equipment factored models and operating costs were determined using additional factors. This case study shows that these methods are easy to use in early stages of a project. Under these assumptions, it was found that the continuous plant is more profitable.

INTRODUCTION

The ultimate goal of all investments is to maximize the economic benefits. The cost of producing a product must not exceed its market price in order to be able to make a profit. The total product cost involves several aspects, as it can be seen in Figure 1.

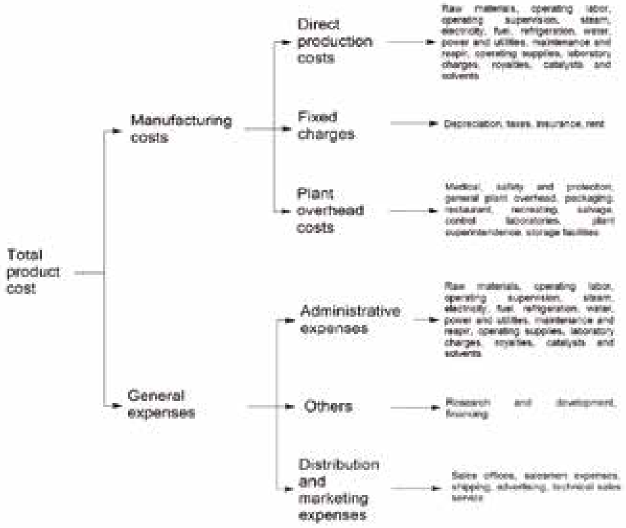


Figure 1. Total product cost estimation (1).

Estimating costs in early stages of a project is not a trivial task (2). New technologies can make this task even more difficult due to lack of experience and information (2, 3). Both overestimating and underestimating have a negative impact on the project. Taking into consideration the inherent inaccuracy of cost estimation, sensitivity analysis can be used. Sensitivity analysis allow to improve the robustness of the estimations.

COST ESTIMATION

There are five different classes of capital cost estimations according to the Association of Advancement of Cost Engineers (AACE), which can be seen in Table 1.

Class	Degree of Project Definition	Usage	Methodology	Accuracy Range
Class 5	0% - 2%	Concept screening	Capacity factored or parametric models	Low: -20% to -50% High: +30% to +100%
Class 4	1% - 15%	Study of feasibility	Equipment factored or parametric models	Low: -15% to -30% High: +20% to +50%
Class 3	10% - 40%	Budge authorization or control	Semi-detailed unit costs	Low: -10% to -20% High: +10% to +30%
Class 2	30% - 70%	Budget control	Detailed unit costs	Low: -5% to -15% High: +5% to +20%
Class 1	70% - 100%	Construction	Detailed unit costs	Low: -3% to -10% High: +3% to +15%

Table 1. Cost estimation classification matrix (4).

Capacity factored estimates are extrapolated data from existing plants (5). Capacity factored estimates can be calculated with the following equation (4):

$$Cost_B = Cost_A \left(\frac{C_B}{C_A}\right)^{\alpha}$$ Eq 1.

in which $Cost_B$ and $Cost_A$ are the cost of plant A and B, C_A and C_B represent the capacity of both plants and α is the exponential factor applied to each specific plant. In some cases, correlations might be represented in graphs but the same principle is applicable (6).

Parametric models are correlations that estimate the cost of equipment based on physical characteristics such as volume, area and diameter (1). The equipment correlations used in this case study are based on Woods (2007) according to the next equation:

$$Cost_B = Cost_A \left(\frac{C_B}{C_A}\right)^{\alpha} \times additional\ factors$$ Eq 2.

in which $Cost_B$ and $Cost_A$ are the cost of the piece of equipment A and B, C_A and C_B represent the physical characteristic of the piece of equipment A and B and α is the exponential factor.

Equipment factored estimates are used to obtain the total capital investment cost by taking the purchased equipment cost and multiplying it by a specific factor (1). This method was initially proposed by Lang and is commonly used in early stages of a project (1). Several other factors have been proposed, being Woods factor the latest one (3, 6).

Equipment costs are not constant and vary in time. Chemical Engineering Plant Cost Indexes (CEPCI) are factors which can be employed in order to determine the present cost of a plant or equipment based on previous data (6).

Operational costs can also be estimated when information is absent by applying different factors. In this document, the Cost & Evaluation Workbook developed by Timmerhaus was employed in order to determine the operational costs of both plants.

CASE STUDY

Polymerization process

Polymers are mostly produced in batch or semibatch reactors (7, 8). Batch reactors consist of a series of non-value added steps (set up, heating, cooling and cleaning). On the other hand, continuous processes, due to their characteristics allow to improve greatly the space-time efficiency of the process by reducing and/or eliminating dead time (9). Equipment is utilized to a greater extent and in some cases reactions can take place at higher temperatures, which translates into faster reaction rates, lower residence times and smaller equipment (10).

Technical studies have proven that polymerization processes can be performed in continuous manufacturing, although most of these experiments have been performed at lab/micro scale (11-13). Some projects such as the EU-FP7 Project (Flexible, fast and future production processes) have aimed to create modular plant systems for chemical reactions at industrial scale, including polymerization reactions (14). Modular plants are designed as skids, in order to ease movement and transportation. In figure 2, a small modular skid plant produced at Microinnova is presented as an example.

Figure 2. Example of a modular plant – 20 kg/h – 160 t/y.

ASSUMPTIONS

Information in early stages of a project is unknown or incomplete, therefore the following assumptions were made for this case study:

- The useful life of the plant was assumed to be 10 y, with a straight line depreciation.
- The salvage cost of both plants was assumed to be 0 $.
- The total output of the polymerization reactor would be equal to 13.5 t/d.
- The final product would consist of a mixture of 50% solvent and 50% polymer. Annual output would be equal to 8,550 t.
- It was assumed that 2 dosing tanks (2 m^3 and 10 m^3), 1 reactor tank (16 m^3) with its auxiliaries (vertical distillation column, vertical and horizontal condenser, water knock-out drum, overflow tank and vacuum pump), 2 thinning tanks (32 m^3) and 4 pumps would be needed for the batch plant.
- The continuous plant would consist of 4 pumps, 4 heat exchangers, 1 polymerization reactor, static mixers, 1 thin film evaporator and 1 stirring tank (32 m^3).
- The material of construction would be stainless steel, unless stated otherwise.
- The batch plant was assumed to require a total of 7 operators per shift (4 operators needed for 5 batch vessels, 2 operators needed for filtration and 1 substitute in case of loss of personnel).
- Typical labor requirements for batch reactors are 1 operator/unit/shift and for continuous reactors are 0.5 operator/unit/shift (1). Therefore it was assumed that a total of 3 operators per shift would be sufficient for the continuous manufacturing plant.
- The salary of the operators was assumed to be 34 $/h
- The raw material cost was assumed to be 1500 $/t.
- By-products and waste disposal costs were left out of the analysis.
- Total energy requirements considered only pumps and motor drives. It was assumed that the agitator power would be equal to 20 kW for the batch reactor and 8 kW for the smaller tank.
- Maximum heat of polymerization was assumed to be 100 kJ/mol (15).
- It was assumed that the cost of polymerization plants reported in the literature would only be applicable to batch manufacturing plants.

RESULTS

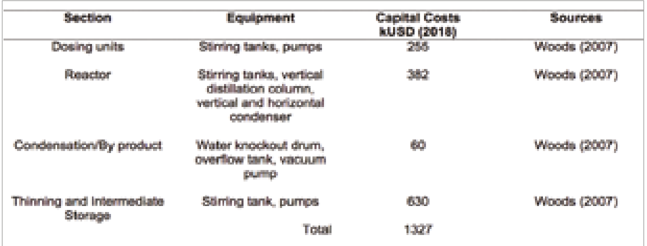
Capital cost estimations

Capacity factor graphs were taken from Garrett (16). It was found that the cost of the plant was approximate 5.5 million USD in 1987 with a CEPCI of 320. Assuming a current CEPCI of 580 (2018), the data was extrapolated to 9.97 million USD.

Parametric and equipment factored models

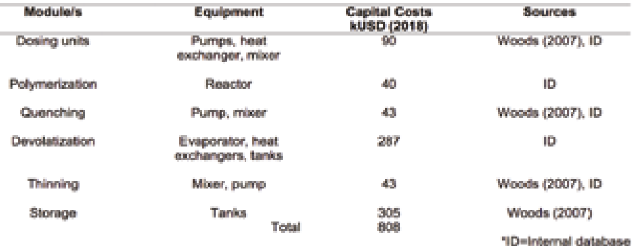
The equipment factored method consists on listing the main equipment. Based on previous correlations, the cost of the equipment was estimated and the appropriate CEPCI factor was applied. In some cases, costs from our internal database were used.

The cost estimation for a stirring tank of 32 m^3 will be used as an example. The cost of a carbon steel stirring tank with a total capacity of 3 m^3 is 75k USD. The exponential factor of this equipment is equal to 0.53 for a CEPCI of 1000. Applying equation 2, it was found that the cost of a 32 m^3 stirring tank would be equal to 152.52k USD for a CEPCI of 580. An additional factor was used in order to take into consideration the material of the equipment, giving a final cost of 305k USD. The same approach was used for the rest of the equipment units and the results are shown in Table 2 and 3.



Section	Equipment	Capital Costs kUSD (2018)	Sources
Dosing units	Stirring tanks, pumps	255	Woods (2007)
Reactor	Stirring tanks, vertical distillation column, vertical and horizontal condenser	382	Woods (2007)
Condensation/By product	Water knockout drum, overflow tank, vacuum pump	60	Woods (2007)
Thinning and Intermediate Storage	Stirring tank, pumps	630	Woods (2007)
	Total	1327	

Table 2. Total purchased equipment cost - Batch polymer plant.

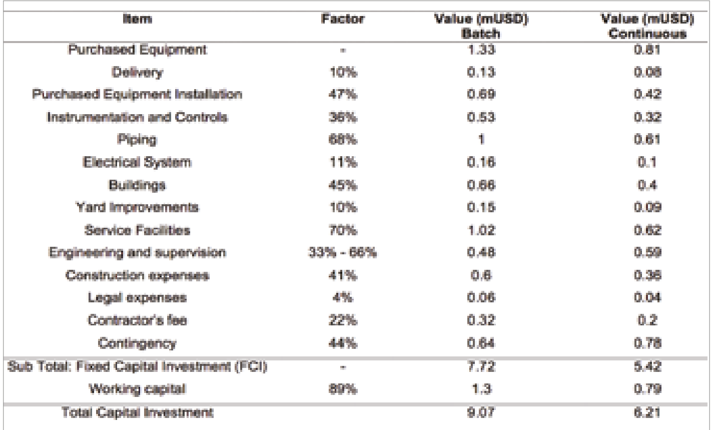


Module/s	Equipment	Capital Costs kUSD (2018)	Sources
Dosing units	Pumps, heat exchanger, mixer	90	Woods (2007), ID
Polymerization	Reactor	40	ID
Quenching	Pump, mixer	43	Woods (2007), ID
Devolatization	Evaporator, heat exchangers, tanks	287	ID
Thinning	Mixer, pump	43	Woods (2007), ID
Storage	Tanks	305	Woods (2007)
	Total	808	

*ID=Internal database

Table 3. Total purchased equipment cost - Continuous polymer plant. *ID=Internal database

Once the total purchased equipment cost had been estimated, the equipment factored method was applied. Two different equipment factored methods were used in order to determine the total cost of the investment. The first method is based on the Lang factor and the results are shown in Table 4.



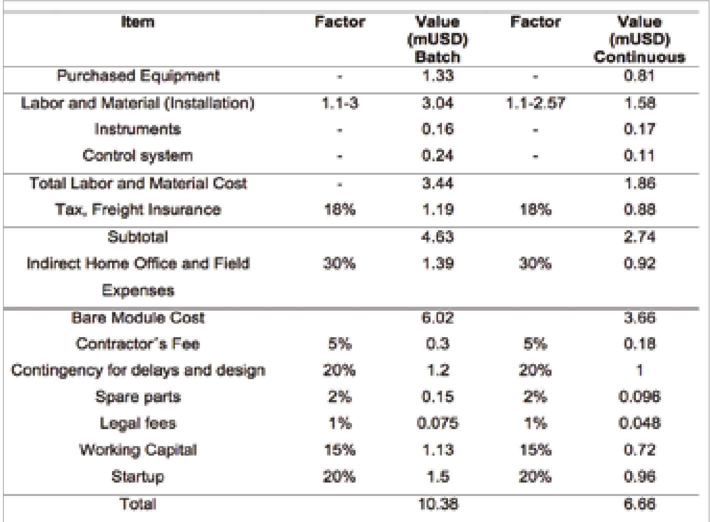
Item	Factor	Value (mUSD) Batch	Value (mUSD) Continuous
Purchased Equipment	-	1.33	0.81
Delivery	10%	0.13	0.08
Purchased Equipment Installation	47%	0.69	0.42
Instrumentation and Controls	36%	0.53	0.32
Piping	68%	1	0.61
Electrical System	11%	0.16	0.1
Buildings	45%	0.66	0.4
Yard Improvements	10%	0.15	0.09
Service Facilities	70%	1.02	0.62
Engineering and supervision	33% - 66%	0.48	0.59
Construction expenses	41%	0.6	0.36
Legal expenses	4%	0.06	0.04
Contractor's fee	22%	0.32	0.2
Contingency	44%	0.64	0.78
Sub Total: Fixed Capital Investment (FCI)	-	7.72	5.42
Working capital	89%	1.3	0.79
Total Capital Investment		9.07	6.21

Table 4. Total capital investment cost using Lang factors (batch vs continuous manufacturing).

The second method was based on Woods (2007). This method takes into consideration the size and complexity of each piece of equipment and it has a higher complexity. The final results are presented in Table 5. Both methods found that continuous manufacturing allows to reduce the total capital investment by approximately 30% as seen in Table 6.

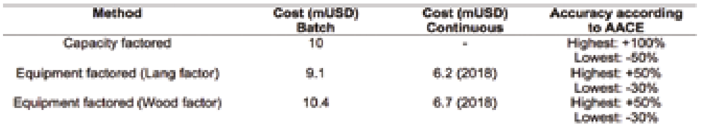
Operational cost estimations

Operational costs were determined for both processes using the Cost & Evaluation Workbook developed by Timmerhaus as seen in Table 7. Based on the total annual product cost and annual depreciation, the total product cost per kg of product was determined. The results are shown in Table 8.



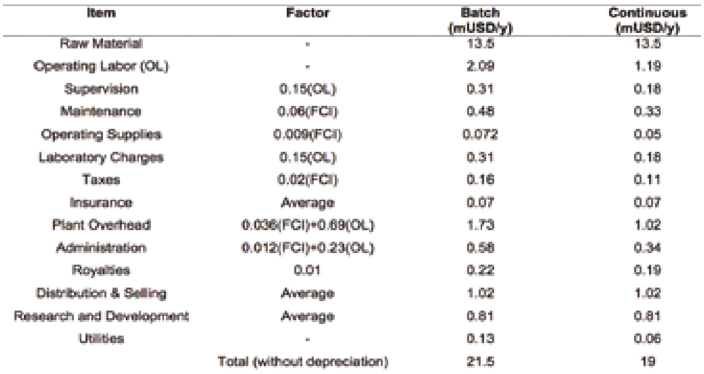
Item	Factor	Value (mUSD) Batch	Factor	Value (mUSD) Continuous
Purchased Equipment	-	1.33	-	0.81
Labor and Material (Installation)	1.1-3	3.04	1.1-2.57	1.58
Instruments	-	0.16	-	0.17
Control system	-	0.24	-	0.11
Total Labor and Material Cost	-	3.44		1.86
Tax, Freight Insurance	18%	1.19	18%	0.88
Subtotal		4.63		2.74
Indirect Home Office and Field Expenses	30%	1.39	30%	0.92
Bare Module Cost		6.02		3.66
Contractor's Fee	5%	0.3	5%	0.18
Contingency for delays and design	20%	1.2	20%	1
Spare parts	2%	0.15	2%	0.096
Legal fees	1%	0.075	1%	0.048
Working Capital	15%	1.13	15%	0.72
Startup	20%	1.5	20%	0.96
Total		10.38		6.66

Table 5. Total capital investment cost using Wood factors (batch vs continuous manufacturing).



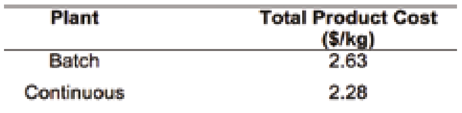
Method	Cost (mUSD) Batch	Cost (mUSD) Continuous	Accuracy according to AACE
Capacity factored	10	-	Highest: +100% Lowest: -50%
Equipment factored (Lang factor)	9.1	6.2 (2018)	Highest: +50% Lowest: -30%
Equipment factored (Wood factor)	10.4	6.7 (2018)	Highest: +50% Lowest: -30%

Table 6. Total capital investment cost comparison.



Item	Factor	Batch (mUSD/y)	Continuous (mUSD/y)
Raw Material	-	13.5	13.5
Operating Labor (OL)	-	2.09	1.19
Supervision	0.15(OL)	0.31	0.18
Maintenance	0.06(FCI)	0.48	0.33
Operating Supplies	0.009(FCI)	0.072	0.05
Laboratory Charges	0.15(OL)	0.31	0.18
Taxes	0.02(FCI)	0.16	0.11
Insurance	Average	0.07	0.07
Plant Overhead	0.036(FCI)+0.69(OL)	1.73	1.02
Administration	0.012(FCI)+0.23(OL)	0.58	0.34
Royalties	0.01	0.22	0.19
Distribution & Selling	Average	1.02	1.02
Research and Development	Average	0.81	0.81
Utilities	-	0.13	0.06
	Total (without depreciation)	21.5	19

Table 7. Annual total product cost.



Plant	Total Product Cost ($/kg)
Batch	2.63
Continuous	2.28

Table 8. Total product cost.

Sensitivity analysis

A sensitivity analysis was performed as seen in Figure 3. It can be seen that the raw material has the highest impact on the total product cost. On the other hand, the initial capital investment has the lowest impact on the total product cost. Operating labor costs have a greater impact than capital costs, which means that defining the amount of operators needed is more critical to the project than the total capital investment cost.

In figure 4, a general overview of the total product costs is presented without taking into consideration the raw materials costs, which would be equal for both plants. It can be seen that most of cost savings come from operating labor and supervision and plant overhead.

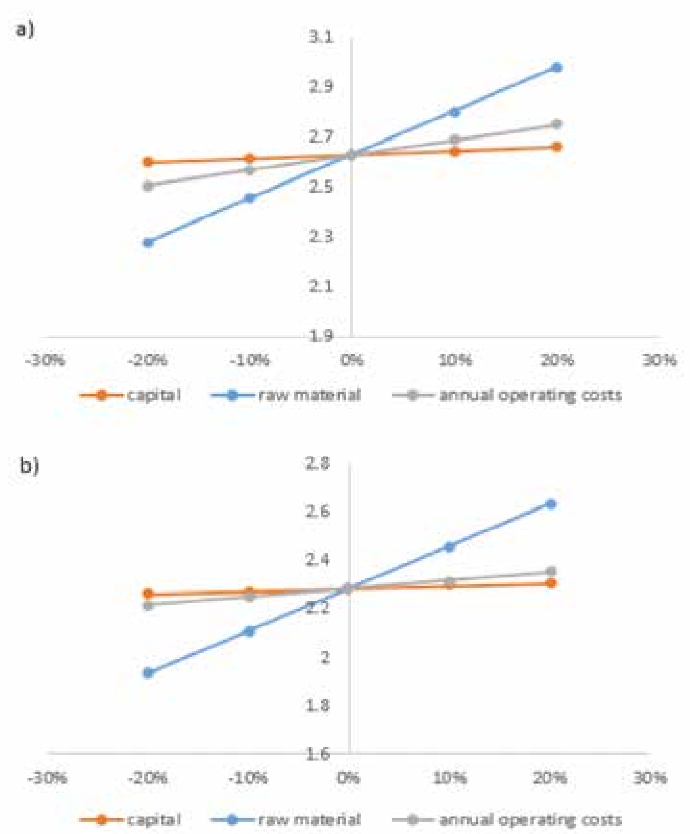


Figure 3. Sensitivity analysis – Total product cost ($/kg) a) Batch process b) Continuous process.

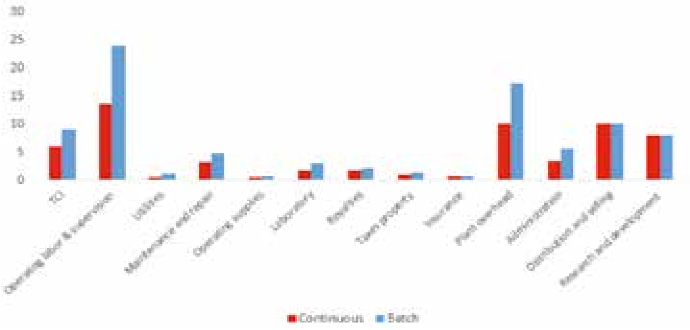


Figure 4. Total costs (10 years), without considering depreciation and/or inflation.

CONCLUSIONS

An economic analysis in early stages of the project was performed using different methods. It was found, that the methods are easy and quick to apply. Under the presented assumptions, it was found, that the continuous manufacturing plant would be more profitable, therefore the next project steps would require to evaluate the technical feasibility of these assumptions, including the operational labor costs.

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Project website: http://cosmic-etn.eu/

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